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Title of Research: **Multiwavelength Observations of Unidentified High Energy Gamma-Ray Sources**

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Multiwavelength Observations
of Unidentified High-Energy Gamma-Ray Sources

Annual Status Report

As was the case for *COS B*, the majority of high-energy (> 100 MeV) γ-ray sources detected by the EGRET instrument on GRO are not immediately identifiable with catalogued objects at other wavelengths. These persistent γ-ray sources are, next to the γ-ray bursts, the least understood objects in the universe. Even a rudimentary understanding of their nature awaits identifications and follow-up work at other wavelengths to tell us what they are. The as yet unidentified sources are potentially the most interesting, since they may represent unrecognized new classes of astronomical objects, such as radio-quiet pulsars or new types of AGNs.

This two-year investigation is intended to support the analysis, correlation, and theoretical interpretation of data that we are obtaining at X-ray, optical, and radio wavelengths in order to render the γ-ray data interpretable. According to plan, in the first year we concentrated on the identification and study of Geminga. The second year was devoted to studies of similar unidentified γ-ray sources from the first EGRET catalog (Fichtel et al. 1994). Our efforts are concentrated on the sources at low and intermediate Galactic latitudes, which are the most plausible pulsar candidates.

These are truly unidentified sources. The positions were screened for known counterparts at other wavelengths. Period searches in the γ-rays were negative for all plausible radio pulsar candidates in or near the error circles. Despite the fact that interesting supernova remnants overlap three of the error boxes, there are no obvious X-ray point-source counterparts. If there are new pulsars in these remnants, however, it is not surprising that *Einstein* did not find them: the necessary X-ray observations will need to be at least an order of magnitude more sensitive than the short *Einstein* exposures.

In the absence of substantial additional soft X-ray data which could be used to search for synchrotron emission from young pulsars, or thermal emission from the surface of an intermediate-age neutron star, we are concentrating on using radio surveys to identify EGRET γ-ray sources. Although it is unclear whether or not the preponderance of the new EGRET sources are rotation-powered pulsars, one thing is certain: the predominant high-energy gamma-ray source population of the Galaxy is young. Both the handful of individual identifications (with pulsars and molecular clouds) and the statistical properties of the Galactic plane sources argue strongly for the association of 100 MeV emitters with the Pop I component of the disk. The best tracers we have of this component are radio continuum surveys, the IRAS database, and CO line surveys.

Using the Very Large Array, we generated high resolution, high-sensitivity images of the Galactic plane at three radio wavelengths: 6 cm, 20 cm, and 90 cm. We made 20 cm images spanning a strip along the Galactic plane 140° in length and 1.5° wide (from 340° to 120° in longitude). The section from 350° to 40° longitude was extended to $\pm 1.5°$ in latitude, while the 6 cm survey covered this same longitude range out to $|b| = 0.6°$. The images have an angular resolution of $4''$ and reveal a total of over 4000 discrete sources (Zoonematkermani et al. 1990; Helfand et al. 1992; and Becker et al. 1994). The 20 cm survey is 80% complete to a flux density limit of 20 mJy for sources $\leq 20''$ in angular extent, while the higher frequency survey goes an order of magnitude deeper to 2.0 mJy. Finally, we made a preliminary map of the longitude range 18–35° with $|b| \leq 4°$ at 90 cm. These low-frequency images have an angular resolution of $30''$ and are over a factor of 30 more sensitive than any existing low-frequency survey. Taken together, these surveys provide by far the most complete picture of the radio source populations of the Galaxy ever assembled. In particular, when combined with the IRAS survey data (White et al. 1991) they allow us to identify hundreds of new compact HII regions which define the distribution of the extreme Pop I component of the Milky Way. These radio maps and catalogs form an integral part of our EGRET source identification strategy.

There are a number of reasons why pulsed radio emission might not yet have been detected from young pulsars that are responsible for the unidentified EGRET sources, and there are several other classes of γ-ray emitters which might also have radio signatures. Our radio surveys might overcome many of these difficulties:

Short-period pulsars – Most large-scale pulsar searches have been relatively insensitive to periods $\lesssim 30$ msec and, until recently, no searches covered large areas of the sky with any any sensitivity below 5 msec. We did, however, discover the first millisecond pulsar in a globular cluster by using spectral and polarimetric information derived from continuum data at 90 cm, 20 cm, and 6 cm (Hamilton, Helfand, & Becker 1985; Erickson et al. 1987; Lyne et al. 1987), and our complete coverage of the plane at these frequencies with similar sensitivity will survey a substantial fraction of the volume of the Galaxy for such pulsars. The most striking illustration of the incompleteness of existing pulsar searches at short periods is the recent discovery (Johnson et al. 1993) of a 5.7 msec binary pulsar with a *mean* 0.4 GHz flux density of 0.6 Jy! The spectral information in our multifrequency survey has already allowed us to identify a dozen pulsar candidates and the complete analysis of our 90 cm data will increase this number substantially.

Highly scattered pulsars – Multipath propagation of pulsar signals in the ionized interstellar medium broadens the apparent radio pulse width and, for relatively short periods and/or distant sources, can wash out the pulse completely. Clifton et al. (1986) showed that a high-frequency search of the Galactic plane revealed many highly scattered pulsars missed in previous surveys; several of these had Vela-like periods. Our radio maps could reveal these sources as steep-spectrum objects appropriate for high-frequency pulse-search followup.

Pole-on or large duty cycle pulsars – There is a well-known correlation between pulsar duty cycle and period, with the shorter period objects displaying broader pulses. These large duty cycle objects are more difficult to detect in pulsar searches, but will be undiminished as continuum sources. In addition, the random orientation of pulsar beams suggests that some nearly aligned rotators may have their beams pointed almost directly at Earth, implying little or no modulation of the radio (and perhaps, the γ-ray) emission. Again, a radio continuum source will still be present. The characterization of the radiation from such a source with this unique geometric perspective would be a most valuable guide to theoretical modelling of both the gamma ray and radio emission mechanisms.

Synchrotron nebulae – Just as a few pulsars may be beamed directly at us, many more are expected to have radio beams which never intercept the Earth. Since the gamma-ray emission is likely to emerge over a larger solid angle (Cheng, Ho, & Ruderman 1986), EGRET may register some pulsars for which no stellar radio emission is detectable (Geminga may be such a case, although it may also represent a truly radio quiet pulsar to which the following argument also applies). As young pulsars, however, these objects might be expected to produce surrounding synchrotron nebulae detectable in the radio (Helfand & Becker 1984; Helfand et al. 1989) and/or the X-ray (Helfand & Becker 1984; Cheng & Helfand 1983) bands. Our 90 cm survey is particularly well-suited in its angular resolution to detecting such nebulae and has a sensitivity to see objects nearly $10^{4.5}$ times fainter than the Crab Nebula.

Smothered pulsars – Neutron stars arise from the explosion of massive stars, and most such stars occur in binary systems. In the majority of cases, it is expected that the binary will survive the SN explosion and, as a result, the young pulsar produced will be embedded in the HII region and stellar wind of its companion. The plasma frequency is much too high for radio pulses to escape from such a system, although strong gamma-ray emission may still be present.

Accreting binaries – Nonthermal radio emission has been detected from a number of accretion-powered binary systems first identified at X-ray wavelengths. Indeed, the only identified Galactic gamma-ray point source which is not a pulsar is the binary radio and X-ray star LSI +61°303. In addition, Helfand & Becker (1985) have discovered a potentially new class of sources with extended radio emission which may be accretion-powered; both of the original examples were coincident with unidentified COS-B sources. Our complete

90cm images of the plane will be particularly well-suited to finding more examples of this phenomenon with EGRET sources as a guide.

Compact HII regions – Several sources in the COS-B catalog have been tentatively identified as enhancements in the 100MeV Galactic plane emission resulting from the interaction of cosmic rays with molecular clouds. Our 20 cm and 6 cm surveys are providing the first complete census of embedded O-stars in the Galaxy (White, Becker, & Helfand 1991; Helfand et al. 1992). A detailed correlation of the EGRET map of the diffuse emission in the plane with the distribution of star-forming regions may prove as instructive as the correlation with molecular clouds. In addition, Chen and White (1992) have proposed a model for gamma-ray generation in the colliding stellar winds from O-star binaries yielding yet another reason to expect a correlation with compact HII regions.

Supernova remnants – Helfand et al. (1989) have argued that at least 500 SNR (roughly 80% of the total) remain to be discovered in the Galaxy and Li et al. (1991) predict an even higher number of unknown remnants. Our 90 cm survey will make an excellent start on the search for these objects. The recent discovery of a previously unknown remnant around the gamma-ray pulsar PSR 1706-44 (McAdam et al. 1993) is striking evidence for the need to compare all new gamma-ray sources with high-quality, low-frequency radio images.

Accretion from molecular clouds – Some γ-ray sources may be associated with dense molecular clouds. This could result if spinning neutron stars pass through the clouds and generate γ-rays through interaction of the pulsar wind with the dense surrounding medium (Harding 1989). Although the dense medium will probably extinguish the pulsar's direct radio emission, the surrounding H II region which is created by ionizing radiation and particles could be visible in the radio via its thermal free-free emission.

So far, we have found that error circles of 18 of the low-latitude, unidentified EGRET sources have some coverage in one or more of our radio surveys. The following Figures show those error circles superposed on the 6 cm, 20 cm, and 90 cm (327 MHz) source catalogs. The sizes of the symbols are proportional to 2.5 times the logarithm of the flux density. We are currently examining each of the sources for anomalously steep spectral indices, which might indicate a pulsar, or small diameter extent, which would be the signature of a young supernova remnant. So far, we have found that four of the 90 cm radio sources on the periphery of the error circle of GRO J1835–23 are extended ($d < 2'$). However, none of the other EGRET sources covered by the 90 cm survey are associated with this type of extended source. We plan to revise these maps when the new error circles become available from the 2nd EGRET catalog. These will presumably be smaller, with more accurate positions. Then we will begin detailed followup observations and analysis of any interesting candidate radio sources.

REFERENCES

Becker, R.H., Helfand, D.J., White, R.L. & Zoonematkermani, S. 1994, ApJS, 91, 347

Cheng, K. S., & Helfand, D. J. 1983, ApJ, 271, 271

Cheng, K.S., Ho, C., & Ruderman, M.A., 1986, ApJ, 300, 500

Clifton, T.R. & Lyne, A.G. 1986, Nature, 320, 43

Erickson, W.C., Mahoney, M.J., Becker, R.H., & Helfand, D.J. 1987 ApJ, 314, L45

Fichtel, C. E. et al. 1994, ApJS, 94, 551

Hamilton, T.T., Helfand, D.J., & Becker, R.H. 1985, AJ, 90, 606

Harding, A. K. 1989, in Proc. Gamma-Ray Observatory Science Workshop, Goddard Space Flight Center, p. 4-157

Helfand, D.J., Velusamy, T., Becker, R.H., & Lockman, F.J. 1989, ApJ, 341,151

Helfand, D.J., Zoonematkermani, S., Becker, R.H., & White, R.L. 1992 ApJS, 80, 211

Helfand, D.J., & Becker, R.H. 1984, Nature, 307, 215

Helfand, D.J., & Becker, R.H. 1985, Nature, 313, 118

Johnston, S. et al. 1993, Nature, 361, 613

Lyne, A.G., Brinklow, A., Middleditch, J., Kulkarni, S.R., Backer, D.C., & Clifton, T.R. 1987, Nature, 328, 399

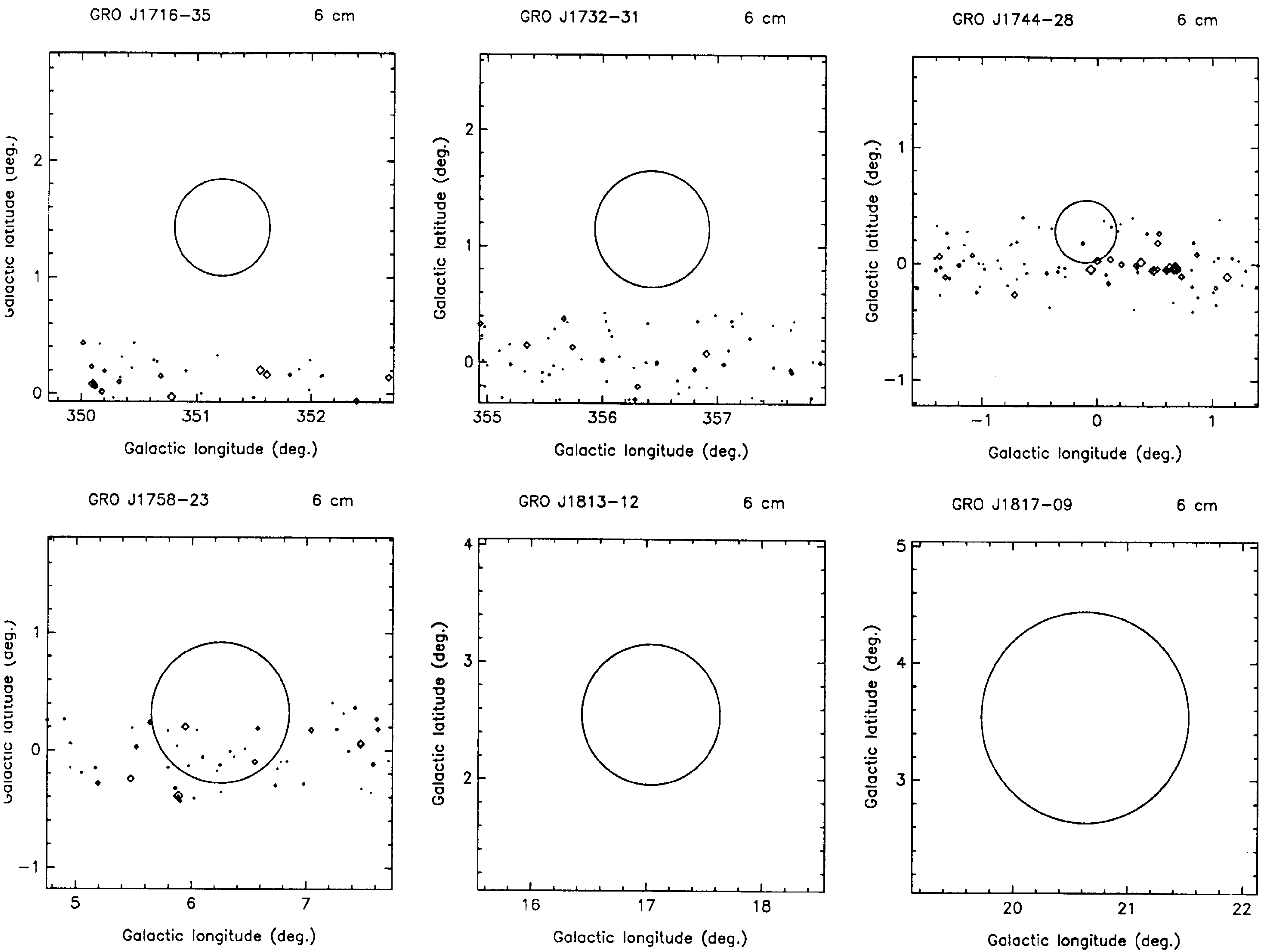
Lyne, A. G., & Smith, F. G. 1990, Pulsar Astronomy (Cambridge: Cambridge Univ. Press), 108

McAdam, W. B., Osborne, J. L., & Parkinson, M. L. 1993, Nature, 361, 516

Ruderman, M., & Cheng, K. S. 1988, ApJ, 335, 306

White, R.L., Becker, R.H., & Helfand, D.J. 1991, ApJ, 379, 564

Zoonematkermani, S. Helfand, D.J., Becker, R.H., White, R.L. & Perley, R.A. 1990, ApJS, 74, 181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6 cm
GRO J1732-31
6 cm
GRO J1744-28
6 cm
GRO J1758-23
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GRO J1813-12
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GRO J1817-09
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Galactic latitude (deg.)
Galactic longitude (deg.)
350
351
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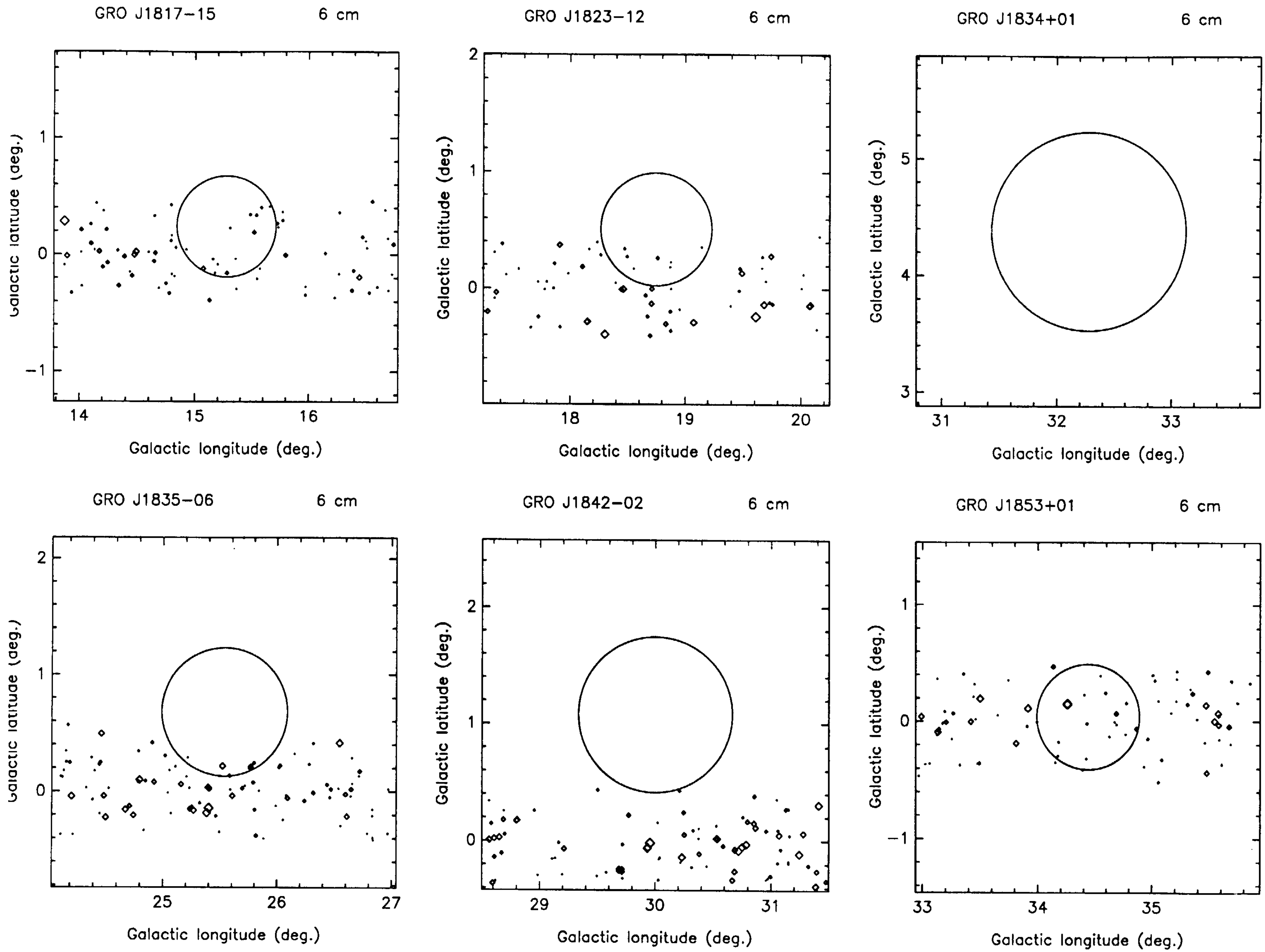

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GRO J1823-12
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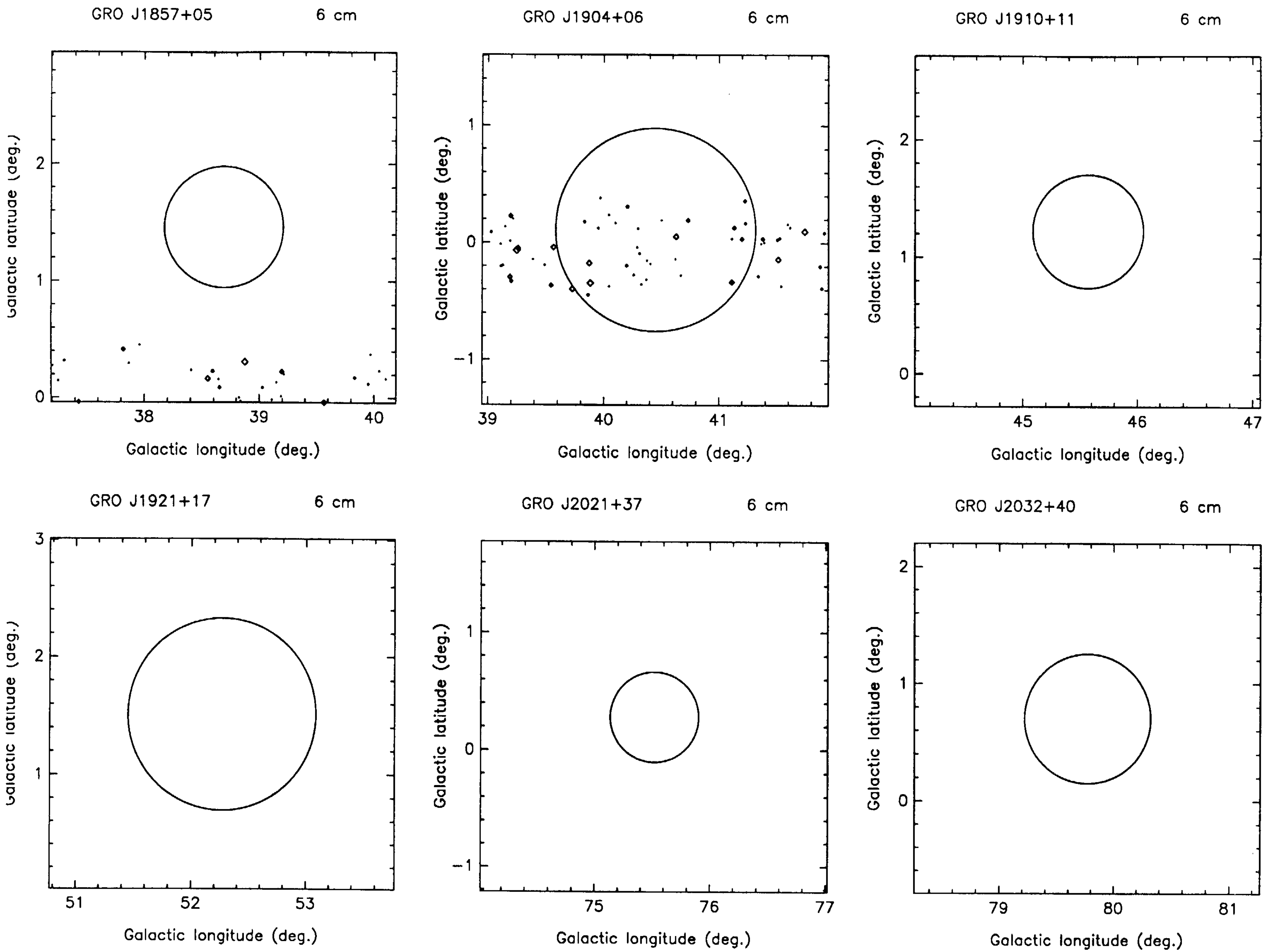
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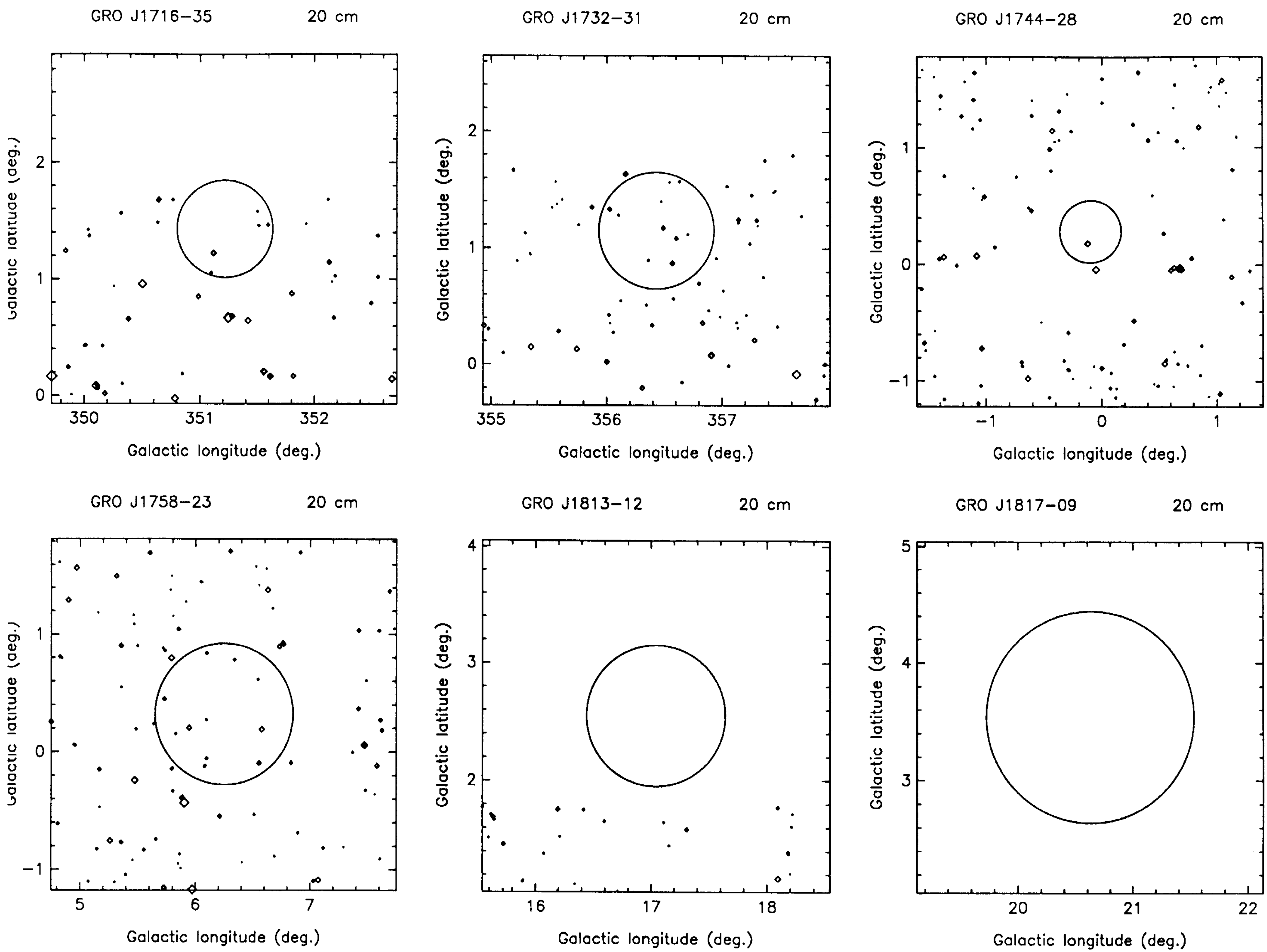

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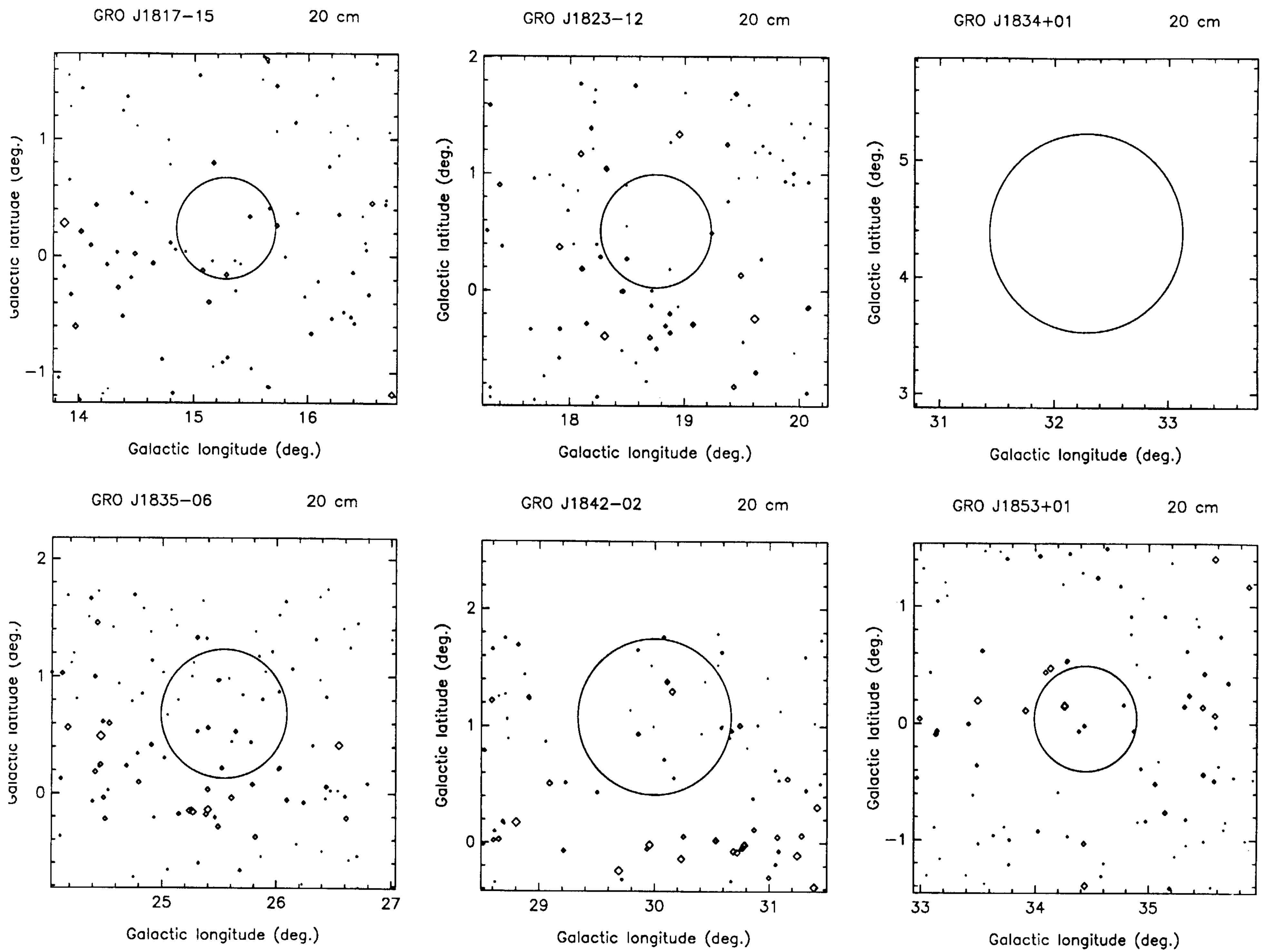

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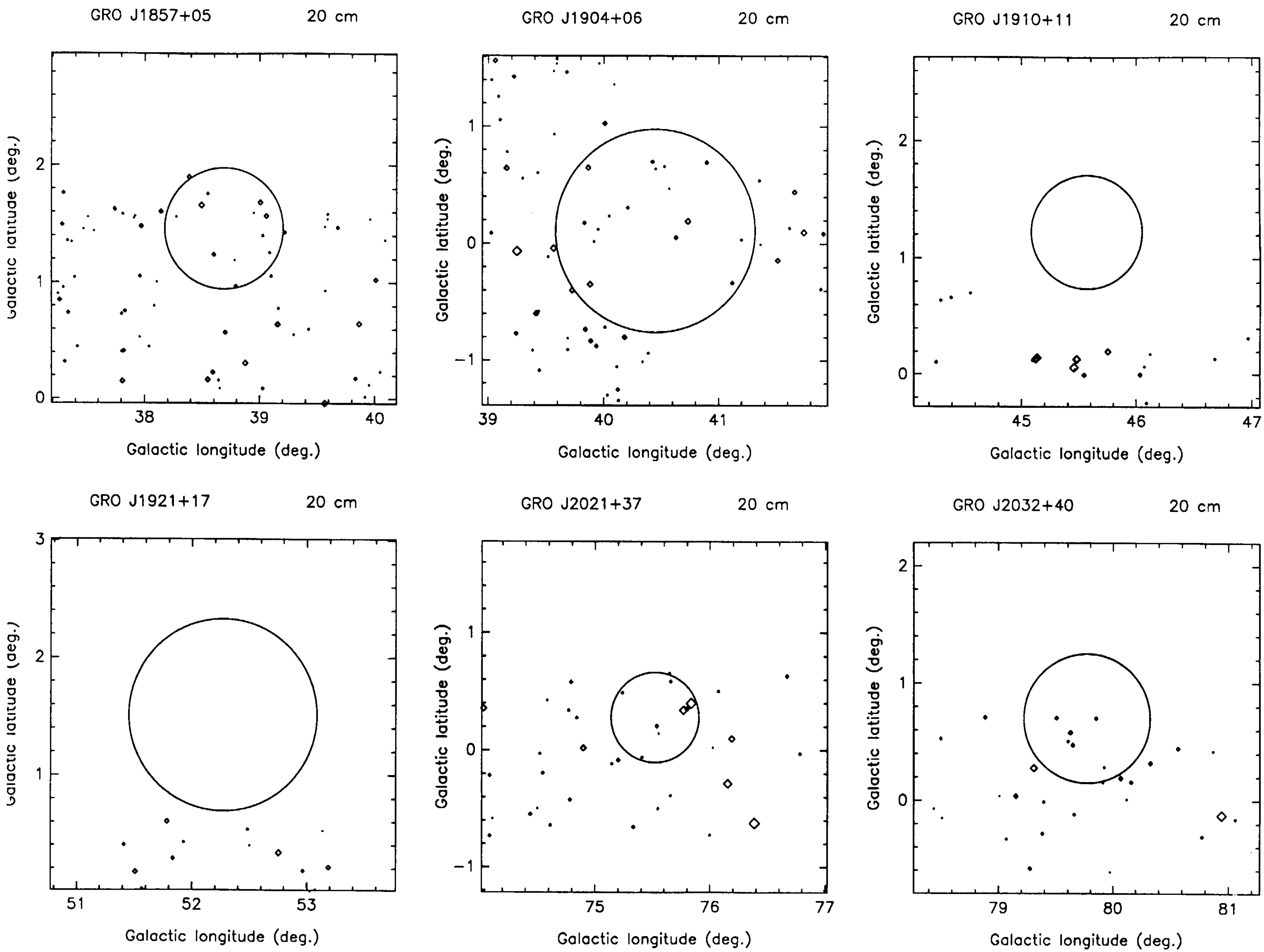
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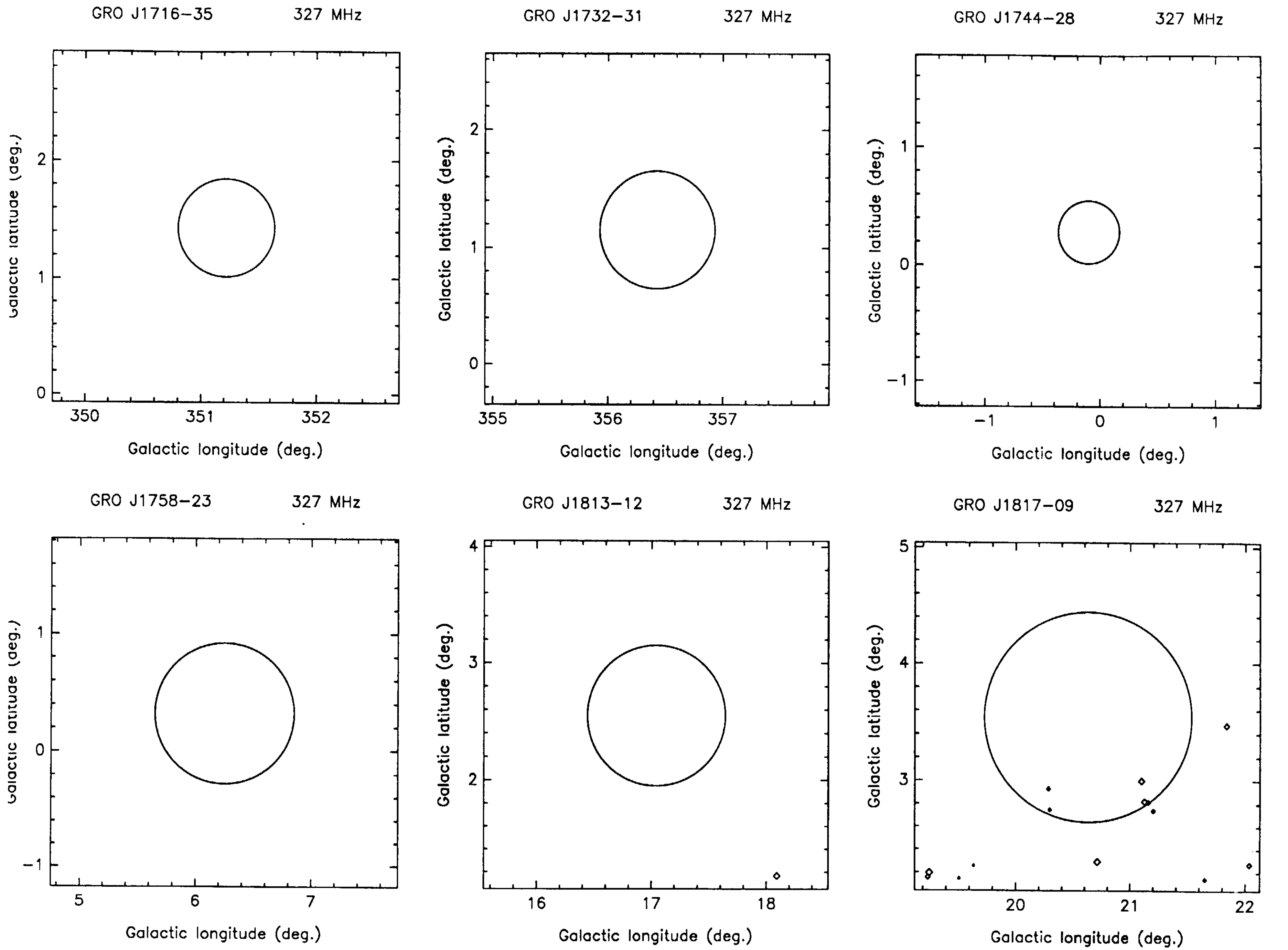
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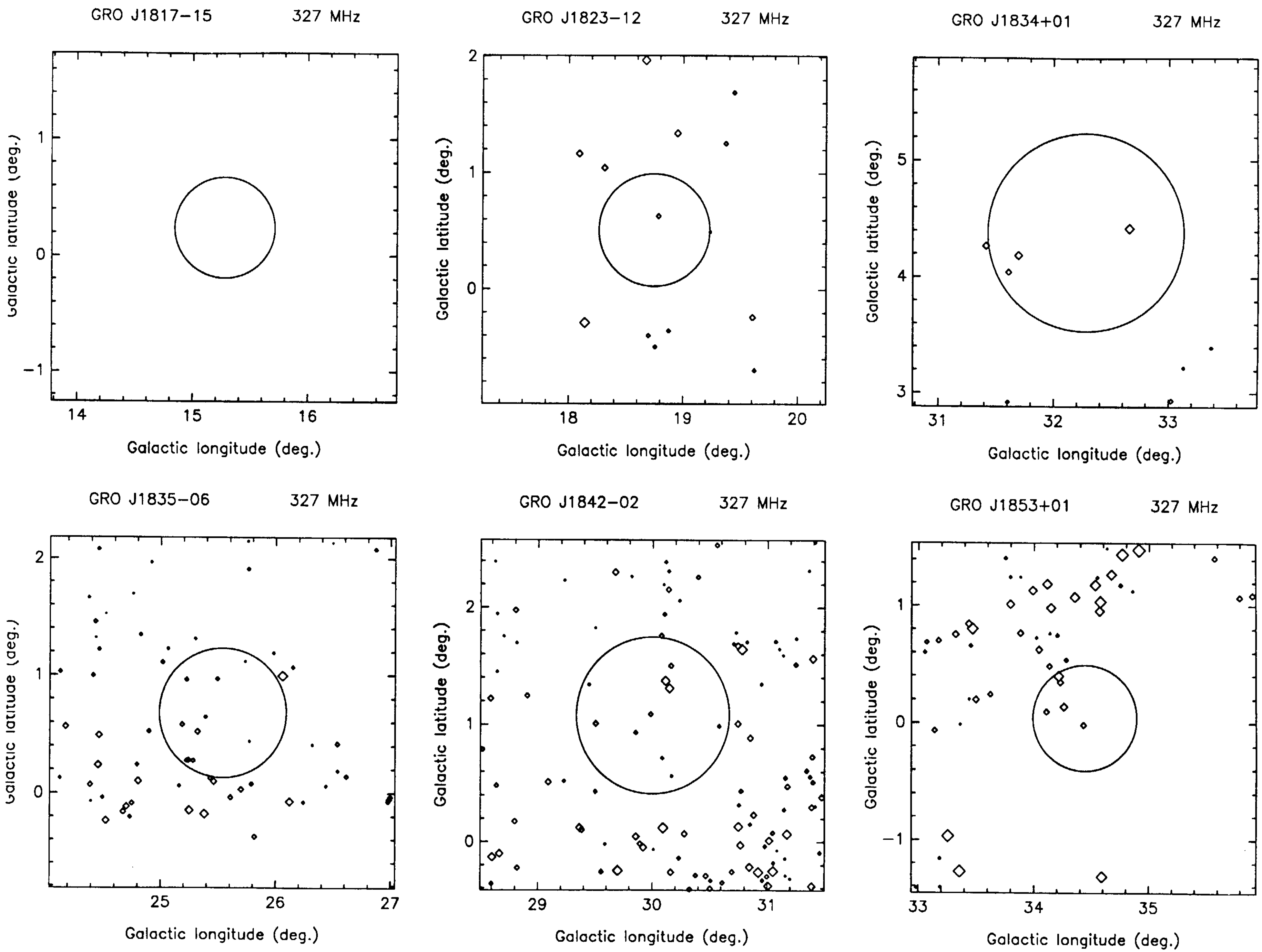
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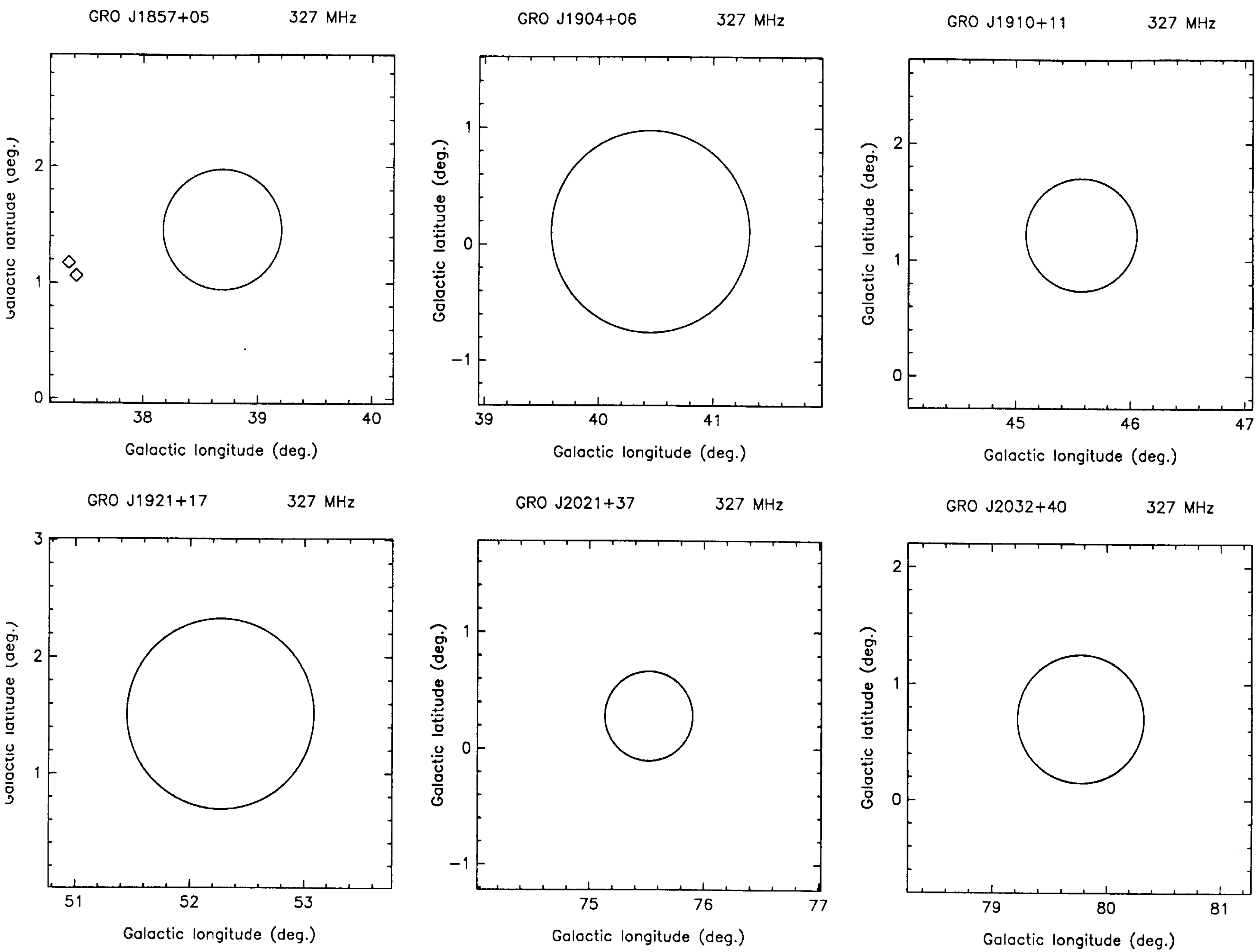
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